Fermi National Accelerator Laboratory

FERMILAB-Conf-83/65-THY
August 1983

# Multiquark Exotics*

Harry J. Lipkin

Weizmann Institute of Science, Rehovot, Israel†

and

Argonne National Laboratory, Argonne, IL 60439

and

Fermi National Accelerator Laboratory, Batavia, IL



*Presented at the Sixth High Energy Heavy Ion Study and Second Workshop on Anomalons, Lawrence Berkeley Laboratory, June 28 - July 1, 1983.

†Supported in part by the Israel Commission for Basic Research.
This work supported in part by the U. S. Department of Energy under contract number W-31-109-ENG-38.

# I. Introduction - Constituent Quarks, Current Quarks and Partons

Experimenters have been working very hard on anomalons by studying secondary interaction in emulsions. However it is still an open question whether this work constitutes convincing evidence that anomalons have any connection to the real world. Similarly we can note that theorists have been working very hard on supersymmetry, supergravity, technicolor, grand unification, solitons, bags, and composite models for quarks and leptons. Here again one can ask where is the convincing evidence that these have any connection to the real world? So far there is not a single piece of such evidence!!!

Unfortunately the history of the search for multiquark exotics has been full of theories which have shown no connection with the real world. A wild goose chase by experimentalists for objects predicted by these theories reached its peak in the baryonium fiasco. We therefore begin this discussion of multiquark exotics by returning to the real world and seeing what real experiments have taught us about hadron structure. We choose models which have proved themselves by giving a reasonable description of these experimental results and by demonstrating predictive power that can be used to investigate the possible existence of multiquark exotics.

There is now overwhelming experimental evidence that hadrons are made of colored quarks bound by interactions with colored gluons. We have every reason to believe that the correct theory for these interactions is QCD. However, we do not know how to calculate the structure and spectrum of hadrons with QCD starting from first principles. We therefore have to use phenomenological models.

The first indications that hadrons were composed of quarks came from the Constituent-Quark model[1] in which the hadron spectrum was calculated by the assumption that hadrons contained constituent quarks in the same way that atoms and nuclei contain constituent electrons and constituent nucleons. The deep inelastic lepton scattering data interpreted with the Quark-Parton model[2] provided completely independent evidence for the existence of quarks. In this picture hadrons consist of elementary point-like "current" quarks which behave like free point particles in deep inelastic scattering. But in addition to the valence quarks which give the hadron its spin and flavor quantum numbers, each hadron also contains an ocean of quark-antiquark pairs and gluon constituents.

The Constituent-Quark model and the Quark-Parton model provide complementary descriptions of hadrons in different domains of hadron physics. In the Quark-Parton model, the properties of quarks are well defined. They are point-like current quarks whose electroweak couplings are described exactly by the Glashow-Weinberg-Salam standard model. However, the way in which these quarks are bound together to make hadrons is completely unknown and the model gives no way of determining the hadron wave functions. These are determined by experiment and expressed in terms of the conventional structure constants, $F_1$, $F_2$ and $F_3$.

In the Constituent-Quark model, on the other hand, the hadron wave function is described completely in terms of the constituent quarks. The baryons consist of three quarks and nothing else, the mesons consist of a single quark-antiquark pair and nothing else, and the wavefunctions are described by various models such as the potential models used in the description of charmonium. However, the properties of the quarks themselves are completely unknown and not specified by the theory. All that is known are the valence quantum numbers which correspond to quantities like electric charge and strangeness. These are conserved in strong interactions and must add up to give the correct total value for each hadron. But other properties such as the quark masses, the quark form factors, and the axial vector couplings are unknown and cannot be predicted in the framework of this model.

The magnetic moment of a hadron in the Constituent-Quark model is completely given in terms of the magnetic moments of the quarks.[3] However these quark magnetic moments are not known from first principles. If they are assumed to be proportional to the electric charges of the quarks, one can write then as Dirac magnetic moments

$$\mu_q = \frac{e\hbar}{M_q C} \tag{1a}$$

where $M_q$ is the quark mass. However the quark mass is not known

$$M_q = ? \tag{1b}$$

This is the characteristic dilemma of the Constituent Quark model. Experimentally measured quantities like hadron magnetic moments are expressed in terms of parameters like the quark masses which are unknown from first principles. These properties, like the structure functions of the Quark-Parton model, are determined from experiment and relations between different experimental quantities are obtained when these unknown quantities can be eliminated.

There are then two approaches to the problem of baryon magnetic moments. One is simply to get relations between baryon moments like the ratio of the neutron moment to the proton moment by eliminating the unknown quark mass parameters.[4] The other approach is to attempt to determine the quark mass parameters from other data on hadrons, namely hadron mass splittings.[5,6,7] This approach has been surprisingly successful in calculating the magnetic moments of the nucleon and the lambda. It has had moderate success in the calculation of other hyperon moments, while leaving some discrepancies and some open questions.[8,9]

The complementary nature of the two models is illustrated by the calculation of $G_A/G_V$ in the two models. The Constituent-Quark model gives the value of $G_A/G_V$ for the nucleon in terms of unknown quark properties

$$(G_A/G_V)_{\text{nucleon}} = \frac{5}{3}\,(G_A/G_V)_{\text{quark}} = ? \tag{2a}$$

The best that can be done with this expression is to invert it to give the value of $G_A/G_V$ for the quark in terms of the measured data for the nucleon.

$$(G_A/G_V)_{\text{quark}} = \frac{3}{5}\,(G_A/G_V)_{\text{nucleon}} \tag{2b}$$

In a sense, this relation (2) is complementary to the determination of the structure functions $F_1$, $F_2$ and $F_3$ in the Quark-Parton model. In both models the experimental data are used to determine the properties of quarks or of hadron wave functions which are not given by the model.

In the Quark-Parton model, the value of $G_A/G_V$ for the quark is given as unity by the Glashow-Weinberg-Salam standard model

$$(G_A/G_V)_{\text{quark}} = 1 \quad . \tag{3a}$$

However there is no relation analogous to (2a) because we do not have any hadron wavefunctions from first principles. The value of $G_A/G_V$ for the nucleon is not given in the Quark-Parton model

$$(G_A/G_V)_{\text{hadron}} = ? \tag{3b}$$

Adler and Weisberger obtained $G_A/G_V$ for the nucleon by using PCAC and pion-nucleon scattering data. They took from experiment the information about hadron wave functions needed to calculate the value $G_A/G_V$. In some sense, this is analogous to the calculation of baryon magnetic moments in the Constituent-Quark model using unknown quark parameters whose values are determined from other hadron data, in that case the quark masses determined from hadron masses.

The Quark-Parton model and the Constitutent-Quark model must arise as complementary aspects of the same basic theory which hopefully will come from QCD. But so far no one has succeeded in obtaining either model from first principles using QCD. Gell-Mann has suggested that constituent quarks and current quarks are two different descriptions which should be related by some kind of unitary transformation. However the search for such a transformation has not been very fruitful and it has been very difficult to translate the results from one model into the language of the other.

## II. Why Bag Models Fail to Describe Multiquark Exotics

An intermediate approach between the two models has been provided by the various bag models which consider the hadron as consisting of point-like zero-mass current quarks with valence quantum numbers and a bag. In this approach, the complications of the ocean of quark-antiquark pairs, gluons, etc. are all swept under the rug and into the bag. One might say that in the Constituent-Quark model, these complications are swept into the definition of the constituent quarks, with each constituent quark carrying its share of the ocean gluons, etc. whereas in the bag model the valence quarks are kept as bare current quarks and the additional constituents are all described by the degrees of freedom of the bag. Intuitively this seems to be a very attractive approach. In practice, however, it has not led to any new insight into hadron structure.

The spectroscopy of the low-lying hadrons seems to be adequately described by the degrees of freedom of the Constituent-Quark model in which each valence quark is "dressed" by its share of gluons and pairs and moves as a unit in a manner described by a simple Schrödinger equation and shows no signs of excitation of its internal structure.[10] We know that there must be other degrees of freedom present in baryons and mesons beyond the three quarks and the quark-antiquark pair. In the Constituent-Quark model, these would show up as excitations of the constituent quarks. In the Bag model, these would show up as excitations of the bag or as motion of the valence quarks relative to the bag. So far no experimental evidence has been found for the existence of any of these additional degrees of freedom. All new effects predicted by the Bag Model have led to unsuccessful experimental searches with negative results, the most striking being the baryonium catastrophe.

Many years ago, Yoshio Yamaguchi visited the Weizmann Institute from CERN and gave a seminar summarizing recent developments there. When he was asked whether there had been any thought about the breakdown of QED at small distances, he hesitated for a moment then said "No. Many calculations, no thought." Unfortunately this seems to characterize most of the work with bag models. The main success of the Bag Model is that it has obtained similar results to those of the nonrelativistic quark model in a formulation which is manifestly relativistic. This perhaps shows that the relativistic corrections to the nonrelativistic Quark model are small or are somehow renormalized away by the procedure of adjusting phenomenological parameters like constituent quark masses to fit experimental data. Such renormalization effects have been demonstrated in some simple models.[7] But one would have hoped to get much more from the Bag Model. It has taught us no new physics and has not succeeded in providing any new predictions to be tested by experiment which show the presence of the bag.

In the case of multiquark exotics, the Bag Model has actually led us astray as shown in the case of baryonium. In fact there are two important aspects of the physics of multiquark systems which are left out in the Bag Model.

1. Correlations. One can expect clustering to occur in multiquark systems. It is difficult in the bag framework to describe a system of quarks which separates into two or more localized clusters.

2. The wave nature of hadrons. The bag is semiclassical. A model of a neutron with three quarks and a bag cannot describe neutron diffraction or a two slit experiment. The constraints on the motion of a bag due to the uncertainty principle are not easily included since the bag itself does not carry momentum.

The importance of these two features for multiquark systems is easily seen in the case of the description of the deuteron. The phenomenological picture of the deuteron in nuclear physics is a state of two nucleons interacting with a short range potential and with a tail on the wave function in which the nucleons spend a large part of the time outside the range of interactions. The wave nature of the nucleon is essential for the description of such a state with the tail of the wave function in the classically forbidden region. The question of whether a bound state exists depends upon the delicate balance between the potential energy obtained from the short range interaction and the kinetic energy required by the uncertainty principle when the nucleons are close enough together to feel the effects of the potential. In a Bag Model, where the nucleons are three quarks in a bag, it is very difficult to describe this kind of physics. One part of the wave function has the two bags outside their interaction range. Another part of the wave function must have two overlapping bags. A third part of the wave function must have all six quarks in the same bag. All these parts of the wave function are coherent and quantum effects with relative phases are important.

## III. Why Multiquark States are Not Bound by Color-Electric Forces

The simple Constituent-Quark model, with all its difficulties, does include a proper treatment of the wave nature of the quarks and of the uncertainty principle as well as the possibility of describing states consisting of several separated clusters. These seem to be crucial for the description of multiquark bound states. We therefore use the Constituent-Quark model with two body potentials as the basis for our further analysis of multiquark systems.

Why are multiquark states considered exotic? If the forces between quarks and antiquarks are attractive shouldn't there be bound states with larger numbers of quarks than three quarks and a single quark-antiquark pair? The first answer to this question can be found in Nambu's old mass formula for color singlets.[11] Nambu noted long before QCD that a crude mass formula could be obtained for a system of n-particles, quarks or antiquarks in a color singlet state interacting via the exchange of colored gauge gluons

$$M(n) = n\, m_0 \tag{4}$$

where $m_0$ is a parameter.

Although Nambu simply called this result a linear mass formula for multiquark states, it already suggests that only the quark-antiquark and three quark states are stable. For the color singlet states with n=2, and 3, we obtain

$$M(q\bar{q}) = 2m_0 \tag{5a}$$

$$M(qqq) = 3m_0 \tag{5b}$$

For the exotic four and five body systems we obtain

$$M(qq\bar{q}\bar{q}) = 4m_0 = 2M(q\bar{q}) \tag{6a}$$

$$M(qqqq\bar{q}) = 5m_0 = M(qqq) + M(q\bar{q}) \tag{6b}$$

All larger states are seen to have sufficient mass to break up into two smaller color singlet clusters having the same mass. They will therefore be unstable against such breakup in this crude approximation.

Nambu did not consider the kinetic energies of the quarks nor the spatial variation of the potential in deriving his mass formula. He simply took the quark masses and a constant value for the two body quark potential independent of the spatial wave functions.

A generalization of Nambu's formula is obtained by taking into account the spatial variation of the potential and including kinetic energies.[12] For an n-particle system containing both quarks and antiquarks,

$$V(n) = \frac{1}{8} \sum_{i \neq j} V_{ij} \sum_{\sigma} \lambda_{i\sigma}\lambda_{j\sigma} \tag{7a}$$

where $V_{ij}$ depends on all the noncolor variables of particles i and j and $\lambda_{i\sigma}(\sigma = 1, \ldots, 8)$ denote the eight generators of $SU(3)_{color}$ acting on a single quark or antiquark i. This is directly analogous to the "isospin exchange interaction" for nucleons of isospin 1/2 interacting by exchanging ρ mesons,

$$V(n) = \frac{1}{2} \sum_{i \neq j} V_{ij} \vec{t}_i \cdot \vec{t}_j \tag{7b}$$

where $\vec{t}_i$ is the isospin of particle i and $V_{ij}$ contains the dependence on all other degrees of freedom except isospin. If we assume factorization of isospin from these other degrees of freedom we can write for any n-particle system containing antinucleons and nucleons,

$$V(n) = \frac{V}{2} \left[ \sum_{\substack{all \\ ij}} \vec{t}_i \cdot \vec{t}_j - \sum_i \vec{t}_i \cdot \vec{t}_i \right] = \frac{V}{2} [I(I+1) - nt(t+1)] \tag{8a}$$

where V is the expectation value of $V_{ij}$ integrated over all variables except isospin, I is the total isospin of the system and t is the isospin of one particle; i.e., 1/2 for a nucleon.

For the colored quark interaction (7a) the interaction energy of an n-particle system can be calculated by the same trick used in Eq. (8a) to give

$$V(n) = \frac{V}{2} (C - nc) \tag{8b}$$

where V is the expectation of $V_{ij}$, integrated over the noncolor variables, C is the eigenvalue of the Casimir operator for $SU(3)_{color}$ for the n-particle system and c = 4/3 is the eigenvalue for a single quark or antiquark. These eigenvalues are directly analogous to the SU(2) Casimir operator eigenvalues I(I + 1) and t(t + 1) in Eq. (8a).

The mass of the n-particle state is given by the sum of n times the quark mass, the interaction (8b) and the kinetic energy T. For a color singlet state, C = 0 and

$$M(n) = nM_q + V(n) + T = n(M_q - \frac{cV}{2}) + T \tag{9}$$

This is just the Nambu formula (4) with an additional kinetic energy term. Again we see that there are no bound multiquark states. When two color singlet hadrons are brought together eq. (9) shows that their potential energy is unchanged. Their kinetic energy must be increased by the localization of the two particles as a result of the uncertainty principle. Thus any color singlet state of more than four particles will have a larger mass than the two color singlet clusters into which it can decay by breakup.

The factorization of color from the other degrees of freedom assumed in deriving eqs. (8) and (9) is automatic for the quark-antiquark and three quark systems where the color coupling is unique for a color singlet state. This no longer holds for multiquark systems and the possibility exists that states of lower mass than that given by eq. (9) could be obtained by introducing correlations between color and the other degrees of freedom. These effects were first investigated for the $(qq\bar{q}\bar{q})$ system where there are two independent couplings to make an overall color singlet.[12] For this system, the interaction (7a) is a nontrivial 2 x 2 matrix in color space. It was shown by diagonalizing this matrix that there were no exotic bound states for well-behaved spin-independent potentials where the criterion for well-behaved included all the commonly used potentials like Coulomb, harmonic oscillator, Yukawa, etc.

The conclusion from this treatment was that color singlet hadrons are color-electric neutral objects and behave like neutral atoms. There are no strong color-electric forces between color-singlet hadrons.

## IV. Color Magnetic Forces and Color-Spin Exotics

The color-magnetic forces introduce the possibility of bound states produced by color-spin correlations.[13] A simple picture of a such a bound state is seen by examining what happens when two kaons are brought together so that the quarks in one kaon can feel the interactions due to the quark-antiquark pair in the other kaon. Our results (8) and (9) show that there is essentially no effect from the color-electric forces. This is confirmed by the experimental observation that the binding energy of the deuteron is very small and there is no evidence for any larger color-electric effects. However energies of several hundred MeV are seen to be available from the hyperfine interaction since flipping a spin in either kaon to make a $K^*$ instead of a kaon costs an energy of 400 MeV.

In the system of two kaons where each kaon is in a spin-zero color singlet state, the hyperfine energy within each kaon is minimized while the hyperfine interactions between the quark or antiquark in one kaon and the quark or antiquark in the other average to zero. However recoupling color and spin can gain binding energy from the hyperfine interaction between pairs in the two different hadrons at the price of losing energy in the interaction between the quark and antiquark in the same kaon. It has been shown that there is a net gain in hyperfine energy by recoupling in certain cases and that therefore there is a possibility of having bound multiquark states.[13,14,15,16]

Jaffe first showed that the lowest multiquark states in the light quark sector are "crypto-exotic" and do not have exotic quantum numbers.[13] This makes it difficult to prove experimentally that they are indeed four-quark states rather than ordinary mesons. However, Jaffe's result was shown to break down when there are more than three flavors.[14] In the charm sector the lowest-lying four quark state can have exotic quantum numbers if all four constituents have different flavors; e.g. $(cs\bar{u}\bar{d})$. Such exotics would provide striking and convincing signatures for multiquark states, but so far none have been found.

For more detailed calculations we use the potential model with the interaction (7a) including the spin dependent forces. As discussed above, bag model calculations are useless because they cannot treat the effects of correlations and of the uncertainty principle applied to the motion of bags in any simple way.

A phenomenological approach was tried in which the parameters of the interaction (7a) could all be determined from experiment with a minimum of model dependence.[15] Consider the case of two mesons (e.g. $K\bar{K}$) brought together to make a four particle wave function like an $\alpha$-particle. We assume that the change in color-electric energy is negligible and investigate the optimum coupling of color and spin to minimize the color magnetic energy. We choose a wave function in which the spatial wave function for any pair in the four body system is the same as in a meson. The matrix elements of the hyperfine interaction are obtained directly from the experimental hyperfine splittings observed in the meson spectrum.

If such an α-particle-like wave function were shown to have a lower mass than two mesons, this would prove the existence of a bound state by the variational principle even though the α-particle-like wave function chosen may not be the best or the correct wave function. However the results showed that the gain in hyperfine potential energy by recoupling spins was not quite enough to overcome the kinetic energy required to bring two mesons together, thus indicating that the α-particle wave function is not bound.

V. Can These be Bound Multiquark Clusters?

The question then arises whether a slightly better wave function might give a bound state. However there is no way of getting matrix elements of the interaction directly from experimental data for spatial wave functions different from those in the mesons. Some model must be assumed to make definite predictions. But it is already clear at this stage that any bound state will be barely bound and therefore very close to threshold. The $\delta$ and $S^*$ scalar mesons are candidates for such bound states of the $K\bar{K}$ system since they are both very close to $K\bar{K}$ threshold and the $S^*$ does not couple strongly to two pions. The degeneracy of the isovector state with the isoscalar state decoupled from pions arises naturally in the four-quark state of one strange and one nonstrange pair. In the quark-antiquark system the degenerate isoscalar and isovector states are both nonstrange, like $\rho$-$\omega$ and f-A2 and the even -G state couples strongly to two pions.

Weinstein and Isgur tested this idea using a harmonic-oscillator potential model because of its ease of calculation.[16] Although this potential has peculiar unphysical long range effects,[17] they concluded that their calculation was insensitive to these long range properties. They found by using a variational calculation with a large space of trial wave functions that the $K\bar{K}$ system was the only four-quark system where binding occurred and that the wave function resembled the deuteron; i.e. it consisted mainly of two quark-antiquark clusters separated by a distance which was larger than the size of each cluster. Although their variational trial wave functions included a continuum between α-particle-like states and such cluster states, the variational principle picked out the states having this clustering property.

Their results can also be expressed in terms of a simple phenomenological model for a two meson bound state.[18] Consider a meson-meson scattering problem with the hyperfine interaction replaced by a short range effective interaction in the two-meson space with a strength inversely proportional to the product of the quark masses as indicated by the hyperfine interaction. For a square well potential with a range a, the condition for the existence of a bound state is

$$\frac{MV}{m_1 m_2} > \frac{\pi^2 \hbar^2}{4a^2} \tag{10}$$

where M is the mass of the meson, $m_1$ and $m_2$ are the masses of the constituent quarks in the meson, and U is a parameter specifying the strength of the potential. Substituting constituent quark masses and experimental meson masses into the left hand side of eq. (10) shows a maximum for the case of the kaon where the two quarks are an up quark and a strange quark.

The physics of this maximum is easily seen. For low-mass mesons like pions, the hadron mass in the numerator of the left hand side of eq. (10) is too small; i.e. the kinetic energy required to localize a low mass pion in a bound state is too large. At high masses like those of charm or bottom quarks, the quark masses in the denominator are too large; i.e. the hyperfine interaction is too weak to produce a bound state. Without a model to give the values of the parameters U and a, we cannot say whether there will be bound states. However eq. (10) shows us that the best place to look for them is in the $K\bar{K}$ system and supports the idea that the $\delta$ and $S^*$ scalar mesons are indeed four quark states. In this case their binding energy is so low that eq. (10) shows that there are no other bound four quark states.

How can we test experimentally whether the $S^*$ and $\delta$ are indeed four quark states? Unfortunately, the $(s\bar{s}u\bar{u})$ system can decay by annihilation of the $(s\bar{s})$ pair into the open $\pi\pi$ and $\delta\pi$ channels, even if the state is below the $K\bar{K}$ threshold and cannot decay by breakup. For this reason the charmed-strange exotic configurations $(cs\bar{u}\bar{d})$ and $(cu\bar{s}\bar{d})$ were suggested[14] as better candidates for unambiguous evidence of a four quark structure. These cannot decay by annihilation and must be stable against strong decays if the breakup channels are closed. However, the Weinstein-Isgur calculation[16] with the result (10) shows that if the $K\bar{K}$ system is barely bound, the the DK system is unbound and might be observed as an exotic resonance but not as a bound state.

The $S^*$ and $\delta$ might be "mini-anomalons" with a shorter mean free path in nuclear matter than $q\bar{q}$ mesons. If they are indeed larger structures looking like two mesons separated by a distance large compared to the size of an individual meson one would expect that they would be absorbed much more quickly in nuclear matter than ordinary $q\bar{q}$ mesons and that this might be detected in experiments on complex nuclei.[18] For example, these mesons going through a nucleus could produce a hypernucleus and a kaon

$$(\delta, S^*) + (Z,A) \rightarrow {}_{\Lambda}(Z,A) + K^0 \qquad (11a)$$

$$(\delta, S^*) + (Z,A) \rightarrow {}_{\Lambda}(Z-1,A) + K^+ \qquad (11b)$$

The structure of these mesons might be tested experimentally by comparing the A-dependence of their production in nuclei with the production of conventional quark-antiquark mesons having the same decay modes. Consider for example, the reactions

$$K^- + p \rightarrow \Lambda + S^* \rightarrow \Lambda + \pi + \pi \qquad (12a)$$

$$K^- + p \rightarrow \Lambda + (\rho, f) \rightarrow \Lambda + \pi + \pi \qquad (12b)$$

$$K^- + p \rightarrow \Lambda + \delta \rightarrow \Lambda + \eta + \pi \qquad (13a)$$

$$K^- + p \rightarrow \Lambda + A2 \rightarrow \Lambda + \eta + \pi \qquad (13b)$$

In the reaction (12) the $\pi\pi$ spectrum should show peaks at masses of the $\rho$, $S^*$ and f. A shorter mean free path in nuclear matter for the $S^*$ implies a qualitatively different behavior in the A-dependence of the $S^*$ peak as compared with the $\rho$ and the f. Similarly the A-dependence of the $\delta$ and A2 peaks in the $\eta,\pi$ spectra of the reactions (13) can be compared.

## VI. Conclusions - Are Anomalons Multiquark Exotics?

So far there is no convincing experimental evidence for any multiquark exotic bound state nor for any exotic resonance. Except for the $\delta$ and $S^*$ there are no candidates for bound states and no firm theoretical predictions waiting to be tested. Exotic resonances may exist in the 1.5-2.0 GeV region and in the charmed sector, e.g. the charmed-strange exotics. The experimental search for multiquark resonances is still open and active.

All this brings us back to the topic of anomalons and the question of whether some kind of multiquark exotic could be responsible for the experimental observations reported here. Could a meson bind to a nucleus in this kind of deuteron-like state to make an exotic anomalon? One might envision a binding of a meson to several nucleons with very short range interactions giving additional binding not present in the meson-nucleon system. However carrying this point of view further encounters difficulties. The long lifetime of anomalons is a serious problem because pions bound to a nucleus should be absorbed much too quickly. Similarly the $K^-$ bound to a nucleus should react to form a hyperon and a pion in a time shorter than the observed anomalon lifetime. A $K^+$ bound to a nucleus would be stable against decays by strong interactions and would have a reasonable lifetime comparable to the kaon lifetime. However there does not seem to be any simple mechanism for producing such a bound state. The s-wave $K^+$-nucleon interaction is known to be repulsive. However perhaps there are other possibilities.

## References

[1]Harry J. Lipkin in Common Problems in Low and Medium Energy Nuclear Physics, (NATO ASI Series B, Physics, vol. 45) Proceedings of NATO Advanced Study Institute/1978 Banff Summer Institute on nuclear theory held at Banff, Canada, August 21 to September 2, 1978, ed. B. Castel, B. Goulard and F. C. Khanna (Plenum, New York) p. 175; R. H. Dalitz, Prog. Part. Nucl. Phys. 8 (1982) 7; H. J. Lipkin, Physics Reports 8C (1973) 173.
[2]A Bodek, These proceedings.
[3]O. W. Greenberg, Phys. Rev. Lett. 13 (1964) 598.
[4]H. Rubinstein, F. Scheck and R. H. Socolow, Phys. Rev. 154 (1967) 1608; J. Franklin, Phys. Rev. 172 (1968) 1807; 182 (1969) 1607.
[5]A. De Rujula, H. Georgi and S. L. Glashow, Phys. Rev. D12 (1975) 147.
[6]H. J. Lipkin, Phys. Lett. 74B (1978) 399.
[7]Isaac Cohen and Harry J. Lipkin, Phys. Lett. 93B (1980) 56.
[8]J. L. Rosner, in High Energy Physics -- 1980, Proceedings of XX International Conference, Madison, Wisconsin, edited by Loyal Durand and Lee G. Pondrom (AIP, New York, 1981) p. 540.
[9]H. J. Lipkin, Nucl. Phys. B214 (1983) 136.
[10]H. J. Lipkin, Phys. Lett. 113B (1982) 490.
[11]Y. Nambu, in Preludes in Theoretical Physics, ed. A. de Shalit, H. Feshbach and L. Van Hove (North-Holland, Amsterdam, 1966) p. 133.
[12]Harry J. Lipkin, Phys. Lett. 45B (1973) 267.
[13]R. L. Jaffe, Phys. Rev. D15 (1977) 267 and 281.
[14]Harry J. Lipkin, Phys. Lett. 70B (1977) 113.
[15]Nathan Isgur and H. J. Lipkin, Phys. Lett. 99B (1981) 151.
[16]John Weinstein and Nathan Isgur, Phys. Rev. Lett. 48 (1982) 659.
[17]O. W. Greenberg and H. J. Lipkin, Nucl. Phys. A179 (1981) 349.
[18]H. J. Lipkin, Phys. Lett. 124B (1983) 509.